Applied Energy 121 (2014) 38–50

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Transient model of a vertical freezer with door openings and defrost effects

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HIGHLIGHTS

- Model of a vertical freezer accounting for the effects of frost formation, door opening and defrosting.
- Validation of the model with experimental results of the evaporator and of the whole freezer.
- Good agreement with experimental data in terms of dynamics and statistical analysis of errors.
- Sensitivity analyses to demonstrate the practical utility of the model.
- Effect of food/medical insertion and of compressor shut off on system performance.

ARTICLE INFO

Article history:
Received 11 June 2013
Received in revised form 2 January 2014
Accepted 25 January 2014
Available online 22 February 2014

Keywords:
Freezer
Temperature
Control
Frost
Defrost
Energy saving

ABSTRACT

Cabinet temperature evolution and energy consumption are two parameters of primary importance for food/medicals preservation and energy savings in cold appliances. In this paper, a transient model of a vertical freezer is developed to study the trend of cabinet temperature and of energy consumption with time, taking also into account door openings, air leakage, frost formation and defrost effect. The model is validated with the experimental data, both with in-house data and with data available in the open literature for frost formation. The results are presented with varying operating conditions, such as air temperature, air humidity, frequency of door opening and defrosting. A qualitative comparison of the trends of air temperature inside the cabinet and of power consumption showed a good agreement between the experimental and simulated profiles; a good agreement was also found in the statistical analysis of errors, with maximum absolute errors on the time averaged temperature of air inside the cabinet of the order of 4 K and maximum relative error on the time averaged power consumption of the order of 4%. Sensitivity analyses are reported as examples to exploit the potential of the model as a tool for design of systems, for settings for defrost parameters and for preventing fault events for food/medical preservation.

1. Introduction

The energy efficiency of refrigerators and freezers for food and medicine preservation is an issue of major importance. Energy databook data for energy consumptions in end-uses in the USA for the year 2010 show that, in the residential sector, refrigeration represents the 3.9% of the site energy consumption and the 6.4% of the primary energy consumption corresponding to the same sector; in the commercial and buildings sectors the values are almost the same [1].

The energy consumptions of light refrigeration appliances are affected by several factors related to ambient conditions (air temperature and humidity), design aspects (mainly thermal insulation, heat exchangers size, compressor displacement), users' behavior (such as number of door openings, duration of door opening and food load) and control (bandwidth of temperature variation, variable/fixed speed of compressor, defrost starting and duration). The effects of these aspects were studied in literature [2–6].

It is well known that cabinet temperature varies with door openings, the duration of door openings and the defrost time [3,5,7]. These factors contribute directly to the frost (formation and melting), and hence influence the energy consumption.

Several researchers have studied the dynamics of frost growth both on simple evaporator geometries [8–12] and on fin-and-tube evaporators [13–24], that can be employed in small and medium scale refrigeration systems. Some studies have dealt with the

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http://dx.doi.org/10.1016/j.apenergy.2014.01.069
0306-2619/

Nomenclature

Latin letters

A	area (m^2)
B	depth (m)
c, c_p, c_v	specific heat (J/(kg K))
D	diameter (m)
$\mathbf{D}$	diffusivity (m^2/s)
f	factor (ad)
G	mass flux (kg/m^2s)
h	heat transfer coefficient ($W/(m^2\ K)$)
H	height (m)
i	specific enthalpy (J/kg),
j	index for the row (ad)
k	thermal conductivity (W/(m K))
K	mass transfer coefficient ($kg/(m^2\ K)$)
L	length (m)
$\dot{L}$	electric power (W)
Le	Lewis number (ad)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
N	integer number (ad)
p	pressure (Pa)
P	pitch (m)
Pr	Prandlt number (ad)
$\dot{Q}$	heat power (W)
r	radius (m)
R	flow resistance ($Pa\ s/m^3$), thermal resistance (K/W)
Re	Reynolds number (ad)
T	temperature (K)
u	specific internal energy (J/kg)
U	internal energy (J)
UA	overall heat transfer coefficient (W/K)
v	specific volume (kg/m^3)
$\dot{V}$	volumetric flow rate (m^3/s)
W	velocity (m/s)

Greek symbols

α	thermal diffusivity (m^2/s)
β	factor (ad)
γ	porosity (ad)
δ	thickness (m)
Δ	difference, change
ε	error (°C, %)
η	efficiency (ad)
θ	time (s)
κ	factor (ad)
ρ	density (kg/m^3)
σ	factor (ad)
τ	tortuosity (ad)
φ	factor (ad)
Φ	relative humidity (%)
χ	factor (ad)
ψ	factor (ad)
ω	specific humidity (kg_v/kg_a)

Subscripts

a	air
amb	ambient
act	active
aux	auxiliary
bypass	related to the bypass
c	cabinet
c-a	related to moist air inside the cabinet
col	collar
cond	condensation
cross	cross-section
def	defrosting
e	external
eff	effective
el	electrical
exp	experimental
ev	evaporator
EV	evaporation
f	frost
fan	related to the fan
fin	related to the fins
food	related to the food
flow	related to air flow
H	heat
hyd	hydraulic
i	internal
ice	ice
in	evaporator inlet
inf	infiltration
j	related to one row
M	metal
m	related to mass
main	related to simulation main period
max	maximum
min	minimum
mod	model
op	opening
out	evaporator outlet
r	row
ref	related to the refrigerant
sat	saturation
sol	solidification
t	tubes
tot	total
v	vapor
vap	vaporization

transient simulation of refrigerators [25–27] and with refrigerator cycling behavior [28]. The simulation study by Bejan et al. [29] demonstrated that the on/off sequence of the compressor was dependent on the frequency and duration of the defrosting period.

Therefore, the aim of this study was to develop a transient model of a professional freezer that is able to predict the dynamics of the air temperature inside the cabinet and of the power consumption, taking into account the door opening, frost formation/melting, defrosting and air leakage. The model was validated with experimental data, focusing on the trends and on the values of the air temperature inside the cabinet, of the metal temperature of the evaporator, of the refrigerant evaporation temperature and of the power consumption, verifying the times of set-point temperature achievement and also of temperature divergence from the set-point value due to frost formation. In particular, a detailed description of the model is reported in the following section, with details on model calibration on the basis of the experimental data and on the solution strategy (Section 2) and of the experimental apparatus (Section 3). Then, the experimental validation and the sensitivity analyses are reported in Section 4.

2. Dynamic simulation model

The refrigerator modeled in this work is composed of a thermally insulated cabinet and a vapor-compression refrigeration loop as depicted in Fig. 1.